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# Transient Studies in Large Offshore Wind Farms, Taking Into Account Network/Circuit Breaker Interaction

Jakob Glasdam, Claus Leth Bak, Jesper Hjerrild, Ivan Arana

**Abstract**—Switching overvoltages (SOV) are considered a possible source of experienced component failures in existing offshore wind farms (OWFs). The inclusion of sufficiently accurate and validated models of the main components in the OWF in the simulation tool is therefore an important issue in order to ensure reliable switching operations.

Transient measurement results in an OWF are compared with simulation results in PSCAD EMTDC and DigSILENT Power Factory, where a user-defined model of the vacuum circuit breaker (VCB) is included, capable of simulating multiple prestrikes during the closing operation.

An analysis of the switching transients that might occur in an OWF will be made on basis of the validated model and the importance of the inclusion of a sufficient accurate representation of the VCB in the simulation tool will be described.

The inclusion of the VCB model in PSCAD greatly improves the simulation results, whereas little improvement is found in DigSILENT.

**Index Terms**—Cable modeling, circuit breaker modeling, DigSILENT Power Factory, model validation, transient studies in offshore wind farms, PSCAD.

## I. INTRODUCTION

IN OWF applications, the consequences of component failure are more severe compared to land based wind farms, due to higher repair costs and lost revenue. [1] Switching overvoltages are a possible cause of component failure observed in Horns Rev OWF 1 as well as in Middelgrunden OWF. [2] Simulations are widely used to identify the overvoltages that might occur in the OWF due to faults and switching operations and in order to verify the design decisions. [1] Validation of OWF component models is therefore an important issue in order to ensure reliable switching studies. It has been shown in [3], [4], that insufficient representation of the radial circuit breaker in the simulation tool is the main contributor to discrepancies between measurement and simulation results for radial energization in OWFs. The vacuum circuit breaker (VCB) is the preferred choice as the radial circuit breaker in OWFs due to its low maintenance requirement and long operation life. [5], [6] Due to the dielectric properties of vacuum, a number of so-called prestrikes are almost inevitable during the closing

operation. The prestrike is a consequence of the decreasing contact gap distance, which facilitates the formation of a low impedance vacuum arc before galvanic contact is established. Because of the working principle of the VCB, there exists a high possibility that the high frequency (HF) inrush current is interrupted at its zero crossing. Depending on the voltage impressed on the contacts, multiple prestrikes might occur. The occurrence of multiple prestrikes is a complex matter and difficult to predict, as the generated voltages and currents depend on many factors such as the dielectric and current interruption properties of the VCB. Furthermore, the multiple prestrikes depend on the surge impedances of the surrounding network, pole scatter, point on wave of closing and so on. This sets up a demand for the inclusion of a sufficiently accurate VCB representation in the simulation tool, capable of taking into account network/circuit breaker interaction during the closing operation. A user-defined representation of the VCB has been implemented in PSCAD EMTDC and DigSILENT Power Factory in [7] and the usability of the models will be discussed in section III and the proposed model will be used in order to investigate the possible occurring SOV in OWFs in section IV.

## II. SYSTEM DESCRIPTION

In this paper the Nysted OWF (NOWF) is taking into consideration as an example. A transient measurement campaign has previously been conducted in NOWF, where GPS synchronized, HF measuring systems were installed at different locations within NOWF as indicated in Fig. 1.

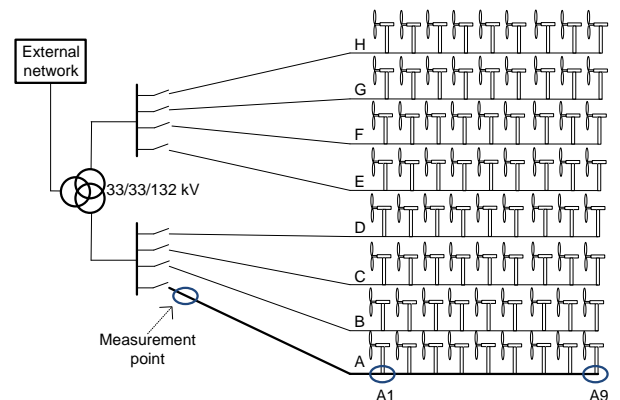


Fig. 1. Schematic of Nysted Offshore Wind Farm. The locations of the measurement system used during the transient measurement campaign are also indicated.

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NOWF consists of  $72 \times 2.3$  MW rated Siemens wind turbines (WTs). The WTs are arranged in a parallelogram formed by eight strings or radials. Nine WTs are connected to each radial. The cable collecting grid is operated at 33 kV and the voltage is increased to 132 kV through the 90/90/180 MVA park transformer, located offshore. Each radial is connected to one of the park transformers two medium voltage (MV) bus bars through a VCB.

The transient measurement is done by energizing radial A, when all other radial are energized. The WTs were not under production during the recording of the transients.

#### A. System Modeling

A model of NOWF has been implemented in DigSILENT and PSCAD based on the information available from the OWF as-built documentation. A schematic of the model can be seen in Fig. 2.

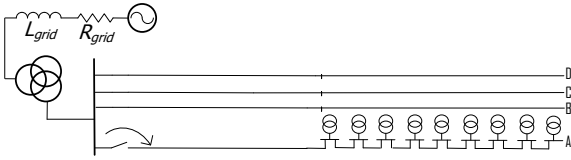


Fig. 2. Schematic of the NOWF network model used in the analysis.

Only the radials connected to the same bus bar as radial A (radial B to D) are included in the model and are each represented by one long cable. The radials in the cable collecting grid are modeled based on geometry and material properties of the cable according to the guidelines in [8], [9]. However, some modifications were found necessary in the cable input parameters, as the simulated wave velocity was found higher in both simulation tools compared to the measurement. This is done by increasing the value of the relative permittivity of the main insulation. The SOV were found to be insensitive to this parameter, whereas the magnitude of the inrush current increased. Furthermore, an unexpected high coupling between the phases was found in DigSILENT, which was limited by separating the phase conductors.

Furthermore, only the transformers on radial A are included in the model using the available standard transformer models in the simulation tools. The export cable system, consisting of a submarine cable and a land based cable, is modeled using the lumped  $\pi$ -model in both simulation tools. The external network is represented by its Thevenin equivalent.

Two model representations of the VCB are considered:

- (i) Build-in switch, which performs one closing operation timed at the instant when the first prestrike in each phase occurs.
- (ii) User-defined VCB model, capable of replicating multiple prestrikes. The model has some similarities with the existing user-defined model in [10], [11] and is described in more details in [7]. Three input parameters are necessary in each phase: The instant of the closing start time ( $t_0$ ), rate of decay of the dielectric strength ( $rdds$ ) in  $V\mu s^{-1}$  of the decreasing contact gap distance and the current quenching

properties ( $CQ$ ) in  $A\mu s^{-1}$  of the VCB before the contacts are making.

#### III. VACUUM CIRCUIT BREAKER MODEL VALIDATION

There is no information available for the VCBs installed in NOWF, hence the input parameters to the VCB model have been adjusted in each phase in order to best fit the simulation results with the measurement results. This is further justified by the fact that the parameters are stochastic by nature as the closing operation can begin with equal likelihood throughout one period of the 50 Hz voltage sine wave and  $rdds$  can range from 25 to  $100 V\mu s^{-1}$ . [12], [13] It was observed in the measurement results in NOWF, that the current is being interrupted each time it crosses zero, hence the value of  $CQ$  has been set to  $600 A\mu s^{-1}$ , as this is the highest measured value for this parameter. [14]

In Fig. 3 is shown the comparison of measurement (red curves) and PSCAD simulation results with the build-in switch (blue) and with the detailed VCB representation (green) for phase B voltages and currents at the platform and the voltages at A9.

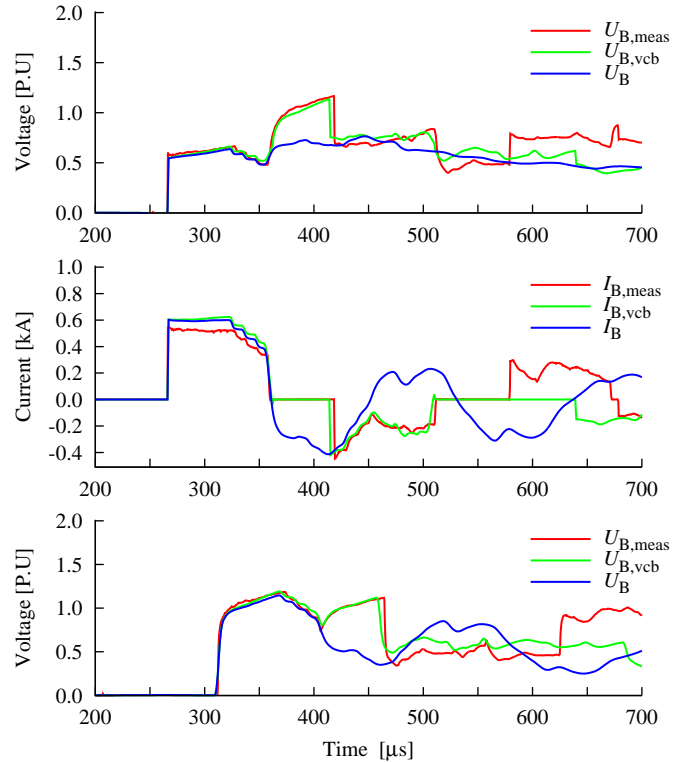


Fig. 3. Comparison of measurement and PSCAD simulation results for phase B voltages and currents at the platform (top and middle plot, respectively) and voltages at A9, when the build-in switch and the VCB model are used.

It is possible to see that the measured current ( $I_{B,meas}$ ) is being interrupted at its zero crossing and therefore appears as 'half waves', which is an indication that multiple prestrikes are occurring. The current interruption causes an energy transfer from the magnetic field associated with the propagating current wave to the electric field associated with the propagating voltage wave in order to comply with energy conservation.

The result is an increase in  $U_{B,meas}$  at the platform, which propagates toward the receiving end of radial A, where it is superimposed on the initial wave.  $I_B$  in the PSCAD simulation using the build-in switch is not being interrupted at its zero crossing and hence the voltage build up at the platform as well as at A9 is not replicated.  $I_{B,vcb}$  is being interrupted at its zero crossing in the PSCAD simulation using the detailed VCB representation. A good agreement can therefore be seen between the measured and simulated waveforms at the two locations for the initial part of the transient. It has not been possible to further improve the simulation results after the initial part of the transient. However, this is considered to be of little importance as the generated SOV are highest in the initial part of the transient. From Fig. 3 it is evident that a sufficiently accurate representation of the VCB is required in the simulation tool in order to replicate the multiple prestrikes inherent to the VCB technology and hence to OWFs, due to the widespread use of the VCB.

A similar improvement in the simulation results by the inclusion of the detailed VCB representation has not been achieved in DigSILENT. This is due to an unexpected high rate of simulated cable discharging after the current is being interrupted. This is illustrated in Fig. 4, where the measured voltage for phase B ( $U_{B,meas}$ ) at A1 is compared with DigSILENT and PSCAD simulation results ( $U_{B,dig}$  and  $U_{B,ps}$ , respectively). A good agreement between DigSILENT and measurement results can be seen in Fig. 4 until  $t \approx 375 \mu s$ , where the current is being interrupted. The voltage on the isolated cable now starts decreasing and the cable is being completely discharged within a few ms, which is not in agreement with real life cable discharging. [7] This high rate of cable discharging has been found for all cable models available in DigSILENT. [7] It can therefore be concluded that DigSILENT is unsuitable for energization studies in OWFs as well as for cable de-energization studies in general.

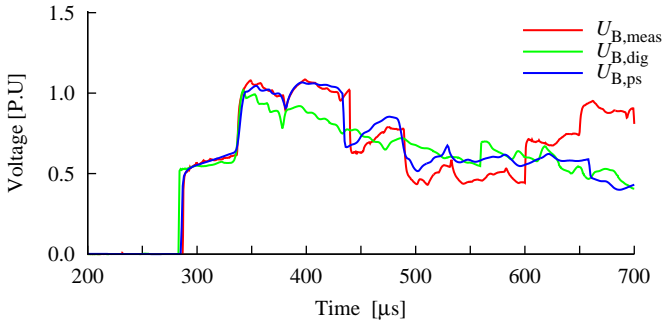


Fig. 4. Comparison of measured phase B voltage at A1 with PSCAD and DigSILENT simulation results using the detailed VCB representation in both simulation tools.

#### IV. TRANSIENT STUDY IN NOWF

The radials in an OWF are supposed to be energized randomly. [5] Different scenarios are investigated in the following in order to give an insight into the SOV that might occur within an OWF using the validated PSCAD model of NOWF, where the network/circuit breaker interaction is included.

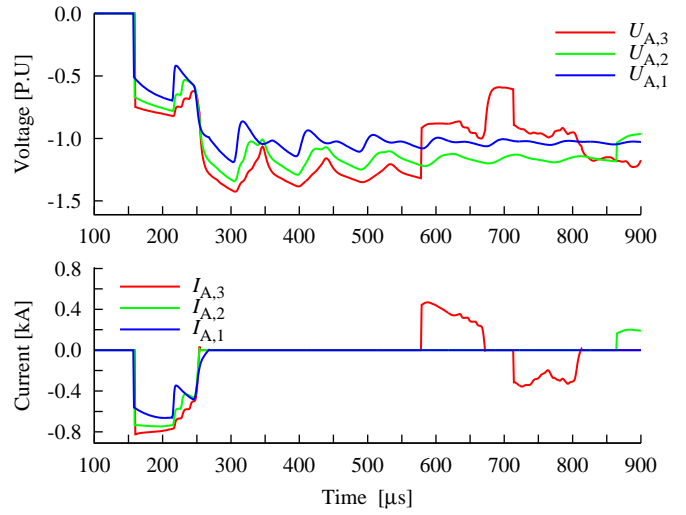


Fig. 5. Simulated platform voltages and currents for the three study cases for phase A. Label numbering corresponds to the number of radials connected when radial A is being energized.

##### A. Energization of Radial A

In Fig. 5 are shown the results of three simulations for phase A at the platform, where the number of radials connected to the same bus bar as radial A (radial B to D, see Fig. 1) are varied. The subscript number in the figure denotes the number of radials connected during the energization of radial A (i.e the subscript 3 is for the situation, where radial B, C and D are connected, 2 is for the situation, where radial C and D are connected and 1 is when only radial D is connected).

The magnitude of the generated SOV in Fig. 5 is increased when more radials are connected. This is due to the impedance ( $Z_{bus}$ ) at the bus bar side of the VCB is lowered when the number of radials connected is increased. The voltage drop on  $Z_{bus}$  is therefore lowered when radial A is being energized.

The peak of the simulated inrush current in Fig. 5 is also increased when more radials are connected. The cables in NOWF are equipped with XLPE insulation with a high value of the relative permittivity ( $\epsilon_r$ ), hence it is possible for sake of simplicity to represent the cable as a capacitor ( $C$ ), where the voltage/current relationship is given by (1). [15]

$$I = C \cdot \frac{dU}{dt} \quad [A] \quad (1)$$

A drop in the voltage at the platform can be seen prior to the current interruption at  $t \approx 250 \mu s$ , which is also occurring in the current traces due to the linear relationship between voltage and current given by the characteristic impedance ( $Z_c$ ) of the cable during the transient.

The voltage drop at the bus bar when radial A is being energized propagates on the radials connected to the same bus bar. The cables on each radial are identical, hence the difference in the traveling times only depends on the length of the radials. The difference in the lengths of radial A to D depends on the location of the first WT on each radial relative to the platform, where D is the shortest and A is the longest radial. This explains the three stepwise decrease in  $U_{A,3}$  in Fig. 5 before the wave propagating on radial A reappears at the

platform and the current is interrupted. Similarly, two stepwise decrease in  $U_{A,2}$  are simulated for radial C and D connected and one drop is simulated for  $U_{A,1}$ , when only radial D is connected. The total voltage drop due to the interaction with the other radials is highest when only radial D is connected, which is due to the higher drop in the bus bar voltage at the instant, when radial A is energized, as explained in the above. As previously explained, the current interruption causes an increase in the platform voltage ( $U_{plat}$ , on the radial side of the VCB), which is simulated in all three cases. The magnitude of the voltage increase is highest for  $U_{A,3}$  and lowest for  $U_{A,1}$ , which is due to the different voltage drops as explained in the above. The frequency of the transients is  $f = 5.3$  kHz for all cases, indicating that the energy into radial A is transferred from the other radials connected. This is the so-called back-to-back energization, which is equivalent to the connection of a capacitor bank to an already energized capacitor bank. [16] A highly simplified schematic of the situation, when energizing radial A to the bus bar, where an already energized cable is connected.  $L_{grid}$  is the Thevenin inductance of the external network. The series impedance of the cable is low, hence the capacitances  $C_A$  and  $C_B$  are almost in parallel and an energy transfer from cable B to cable A is taking place.

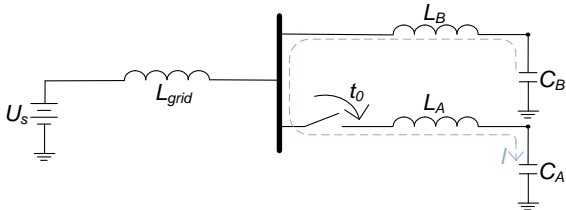


Fig. 6. Simplified schematic of the connection of cable A to the already energized cable B, where losses are neglected.

The frequency of the inrush current in Fig. 6 can be calculated as in (2). [7], [15]

$$f = \frac{1}{2\pi\sqrt{L_A C_A}} \quad [\text{Hz}] \quad (2)$$

$$\approx \frac{1}{4l_{cab}\sqrt{\mu_r \epsilon_r}}$$

where  $\mu_r$  and  $\epsilon_r$  are the relative permeability and permittivity of the cable, respectively.  $l_{cab}$  is the length of the cable. Equation (2) indicates that the frequency of the transients when other cables depends only on the length and materials of the cable.

The situation is different when no cables are connected to the bus bar, as cable A will interact with the external network as shown in Fig. 7.

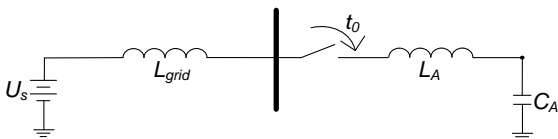


Fig. 7. Simplified schematic of the connection of cable A, when no cables are connected.

The frequency of the transients in the case when no radials are connected is given in (3), where it is evident that  $L_{grid}$  will lower the transient frequency.

$$f = \frac{1}{2\pi\sqrt{(L_{grid} + L_A)C_A}} \quad [\text{Hz}] \quad (3)$$

The simulation results for the case with no radials connected are shown in Fig. 8, where  $f = 3.8$  kHz, which is 28 % lower compared to the situation, when other radials are connected.

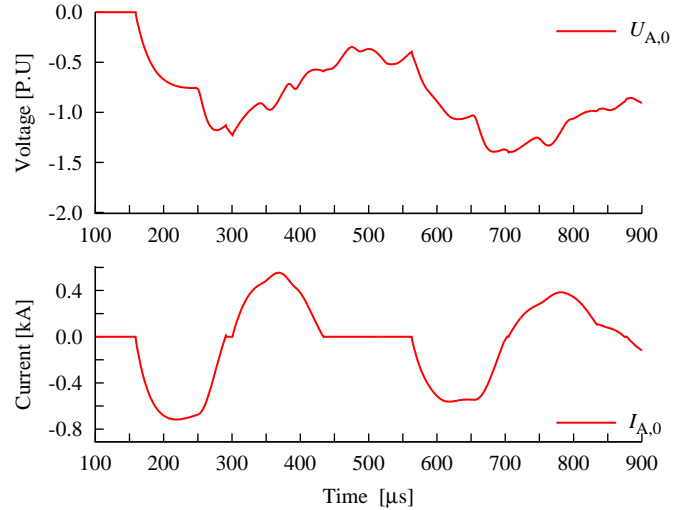


Fig. 8. Simulated platform voltages and currents for phase A when no radials are connected.

## B. Comparison of Different OWF Configurations

The influence of the OWF configuration on the SOV will be investigated in the following, where three cases are considered: (i) Radial A energization, (ii) Radial D energization and (iii) Radial A energization, where the length of radial A is doubled and the lengths of radials B to D are increased in order to maintain the radial inter spacing. Three radials are connected in each case. Case (i) is the same as in the previous section. Case (iii) is the hypothetical case, where the step up transformer is located onshore and hence the radial lengths are increased. In Fig. 9 are shown the initial part of the simulated phase A voltages and currents at the sending end of the radial being energized.

The initial parts of the transients in Fig. 9 are identical in the three cases, which is due to the identical types and number of cables connected to the bus bar in the three cases. Differences can be seen for the traveling wave times and hence the transient frequency, which is due to the different length of the radial being energized in the three cases. The three stepwise decrease in the waveforms for case (i) (red curves) due to interaction with the other radials connected are also occurring in case (iii) (blue curves), whereas they are more attenuated, which is due to the longer traveling distances in this case. The radial interaction is not occurring in case (ii), where radial D is being energized. Because of the shorter length of radial D compared to the other radials, the wave propagating



on this radial will reappear at the platform, where the current is interrupted before the waves on the other radials reappear at the platform.

### C. Point on Wave Influence on the Generated SOV

The most important parameter on the generated SOV is the point on voltage wave (POW). The instant of the contact start closing time is uniformly distributed over one period of the fundamental frequency, which results in an infinite number of switching combinations. Different methods to capture the highest possible SOV do exist, namely the systematic and the statistical switch. [17] However, none of the existing methods are taking into account the possibility of the occurrence of multiple prestrikes, inherent to the VCB technology. A design procedure for a statistical switch, being able to take into account network/VCB interaction is proposed in [7] and further work is expected to be done in this area.

A number of simulations have been carried out in order to investigate the influence of the POW on the generated SOV. This is done by systematically varying the instant  $t_0$ , when the closing operation begins by an increment of 1 ms over one period of the fundamental frequency. The simulations have been done for both VCB representations investigated in the current paper in order to compare the simulation results. The simulations are done by energizing radial A, when radial B to D are connected. The highest case SOV has been captured for each simulation at the platform and at A9 as shown in Fig. 10. The time axis in Fig. 10 indicates the instant, when the closing operation begins in the simulation.

A half wave symmetry of the highest case SOV is evident for both VCB representations in Fig. 10. It is therefore possible to confine  $t_0$  in an interval of 10 ms in a 50 Hz system in order to reduce the computational time. It is suggested in [18], that  $t_0$  can be confined to the peak portion of the voltage wave and for positive values of  $dU/dt$  of the voltage wave, and hence further reduce the computational time. However, this is not in agreement with the measurement results in NOWF, as it

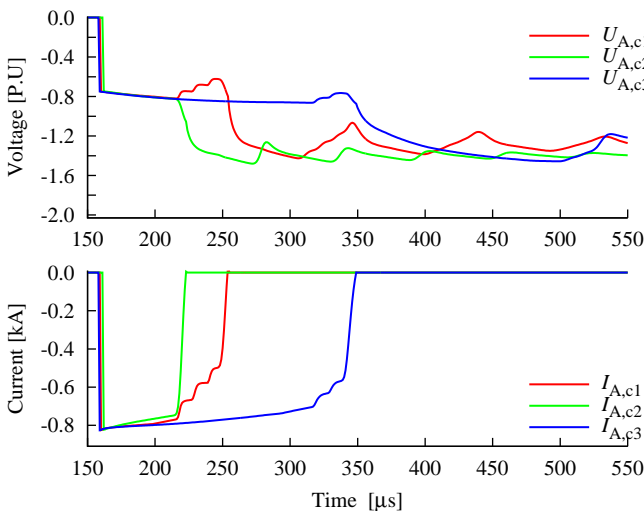


Fig. 9. Simulated sending end voltages and currents for the three study cases for phase A.

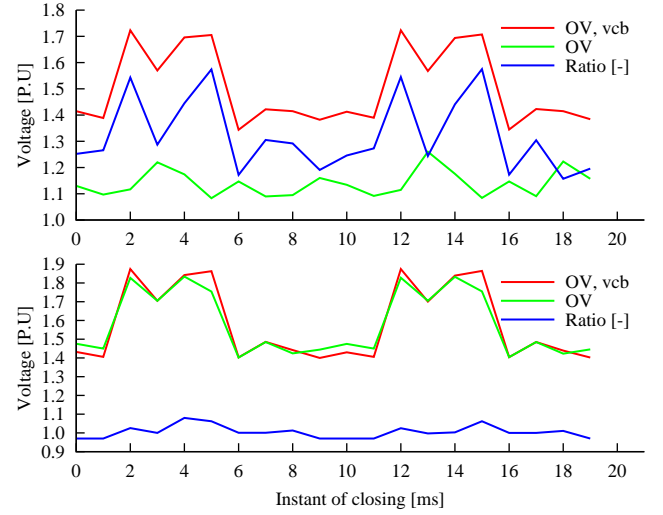


Fig. 10. Simulated case SOV using the build-in switch and the detailed VCB description. Top plot at the platform and bottom plot at A9.

has been found that the multiple prestrikes are occurring for a negative value of  $dU/dt$  for one of the phases during the closing operation. [7] The author therefore proposes that  $t_0$  should be confined to an interval of 10 ms.

It can be seen from the top plot in Fig. 10, that there are large differences in the simulated case OV at the platform using the two VCB representations, the highest difference being 60 %. This therefore stresses out the importance of the inclusion of a sufficiently accurate VCB representation in the simulation tool, as it was found from Fig. 3 that the detailed VCB representation greatly improves the accuracy of the simulation results. Little difference can be observed in the simulation results at A9 in the bottom plot in Fig. 10, which is also in good agreement with Fig. 3. A similar agreement is also found at A1. It can therefore be concluded that a sufficiently accurate VCB representation is required in the simulation tool in order to predict the SOV at the platform, whereas the build-in switch can be used if only the SOV at the wind turbines are investigated.

From Fig. 10 it is furthermore evident that the selected resolution of 1 ms for  $t_0$  is too low, as there are large differences between some of the successive simulation results at both locations. This is true for both VCB representations. This finding implies the importance of the inclusion of a VCB representation, capable of taking into account the randomness of the closing instant, as described in the above.

## V. CONCLUSION

Transient measurement results in NOWF have been compared with simulation results in this paper with emphasis on the radial vacuum circuit breaker, which has previously been found to be the main limitation in the accuracy of simulation results in OWFs. A user-defined representation of the VCB has been implemented in PSCAD EMTDC and DigSILENT Power Factory and the simulation results have been compared with transient measurement results in NOWF, where one of the radials is being energized. The inclusion

of the VCB in PSCAD greatly improves the accuracy of the simulation results, whereas little improvement was found in the DigSILENT simulation results, which was found to be due to an unexpected high rate of cable discharging after current interruption. DigSILENT is therefore found unsuitable for energization studies in OWFs as well as for cable de-energization studies in general.

A transient analysis has been carried out in order to investigate the possible SOV, that might occur in large OWFs during radial energization. It has been found that a sufficiently accurate VCB representation is required in the simulation tool in order to predict the SOV at the platform, whereas the build-in switch can be used if only the SOV at the wind turbines are required.

The magnitude of the SOV is found to increase with increased number of radials connected. The transient frequency is found to be insensitive to the number of connected radials, as long as at least one radial is connected. This indicates the little influence of the external network. The accuracy of the external network becomes important with no radials connected as the frequency is lowered by 28 % compared to the situations with one or more radials are connected. This is due to the interaction with the short circuit inductance of the external network.

The analysis has shown that all possible scenarios should be investigated in the design phase of future OWFs.

#### ACKNOWLEDGMENT

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